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14. ABSTRACT

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Front Tracking on Problems of US Air Force Interests SFFP Final Report

August 30, 2013

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Abstract

We report the collaborative efforts and initiatives on research of three problems which are of potential interests to the US Air Force. We have investigated two problems during the Air Force Summer Faculty Fellowship Program (SFFP) and started the third one. These problems include the study of transonic shock formation on the aircraft wings, parachute inflation, and the simulation of airplane icing tests. Our approach is the front tracking method developed at Stony Brook University. We compared the front tracking simulation on a couple of bench mark problems with AERO Suite and demonstrate that the front tracking code is a cost-free public domain software platform for both research and education on the physics of supersonic and transonic flow around the aircraft wings. We report major progress on the study of parachute inflation through first principle fluid equations and the meso-scale spring-mass model. We proposed an initiative on the numerical study of airplane icing through inter-operable computation of the phase transition module and the incompressible fluid module in the front tracking code.

Keywords: front tracking, airflow, parachute inflation, airplane icing

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1. Introduction

Under the support of the US Air Force Summer Faculty Fellowship Program (SFFP), Xiaolin Li, faculty member of the Stony Brook University, and Bernard Moore, a graduate student of Stony Brook University carried out a research visit to Edwards Air Force Base. During this visit, the visiting faculty member collaborated with Dr. Daniel Reasor and Mr. Keerti K. Bhamidipati in a joint research effort on three problems of potential Air Force interests.

Our approach is through the Lagrangian front tracking method which is an adaptive computational method to follow the dynamic evolution of a discontinuous interface. It represents the interface as a set of topologically connected marker points and uses finite difference method to each smooth subdomain. The discontinuity, or the front, is treated as an interior boundary for the PDE solver in each subdomain. It is known that this method can give high resolution at subgrid level and keep sharp corners with acute angles[2, 3]. Over the last twenty years, Xiaolin Li, in collaboration with his Stony Brook colleagues, has applied this method to many scientific and engineering problems including fluid interface instabilities, fluid structure interactions and phase transition problems. It is our intention the explore opportunities of applying this computational tool to problems of interests to the Department of Defense including both Army and Air Force.

During this research visit, we have performed benchmark tests, collaborated in design of numerical algorithms and proposed for future research problems in three areas. The first problem is the study of supersonic and transonic flow around the aircraft wings. During the visit, we implemented functions to initialize two dimensional wings from the database website of UIUC. The visiting graduate student, Bernard Moore, carried out verification study of front tracking code on supersonic flow around a cylindrical obstacle and compare the distance from the bow shock to the surface of the obstacle with the analytical solution. The verification study extended to different wings, including the F-16 wing in supersonic flow. In subsequent study, we found discrepancy between the front tracking code and solution from AERO Suite on transonic flow. We attributed this to the inaccurate boundary treatment of the front tracking code and will improve the front tracking code.

The second problem is on the modeling of fabric surface using the spring-mass model and its application to the simulation parachute inflation. One important accomplishment we made during this visit is the design and implementation of algorithm to calculate the von Mises stress which is critical for parachute deployment and inflation. We met with Air Force experts who gave us suggestions and recommendations on the validation study of parachute. Under their suggestion, we obtained experimental data from Prof. Jean Potvin the drag force in skydiving experiment of the C-9 personnel parachute. We carried out numerical simulation and compared with the experimental data. The comparison showed agreement on duration and peak drag of the C-9 inflation, but also showed some disagreement in after inflation drag. This comparison study provides vital information on the improvement of the parachute model.

During the visit, we also discussed the potential application of the phase-transition module in the front tracking code to the airplane icing test. This newly developed front tracking capability to compute water freezing and melting, together with the fluid advection will provide a cost-efficient computational platform for the study of aircraft icing.

2. Simulation of Shock Around Airfoil

Iovnovich and Raveh [5] studied the oscillatory shock-buffet of the NACA-0012 and NACA-64A204 airfoils and showed that these oscillations occur and diminish over a range of attack angle in transonic flow. For example, it was shown that at Mach 0.75, the shock-buffet instability for the NACA-64A204 occurs between the onset attack angle of 5.1 degree and offset angle of 8.0 degree. It was observed that shock-buffet onset occurs when the shock is just behind the location of maximum curvature where the surface slope is close to zero.

Our Edwards advisor Daniel Reasor introduced this phenomenon at the beginning of our visit and recommended that we use the front tracking code to study the formation of shock buffet which could help enhance the understanding of airfoil in the transonic regime. Under his suggestion, we implemented the initialization functions for aircraft wings in the front tracking code during the first week and Bernard Moore carried out a series of simulations, first the verification of the code on supersonic flow and bow shock formation, and then the study of transonic shock buffet.

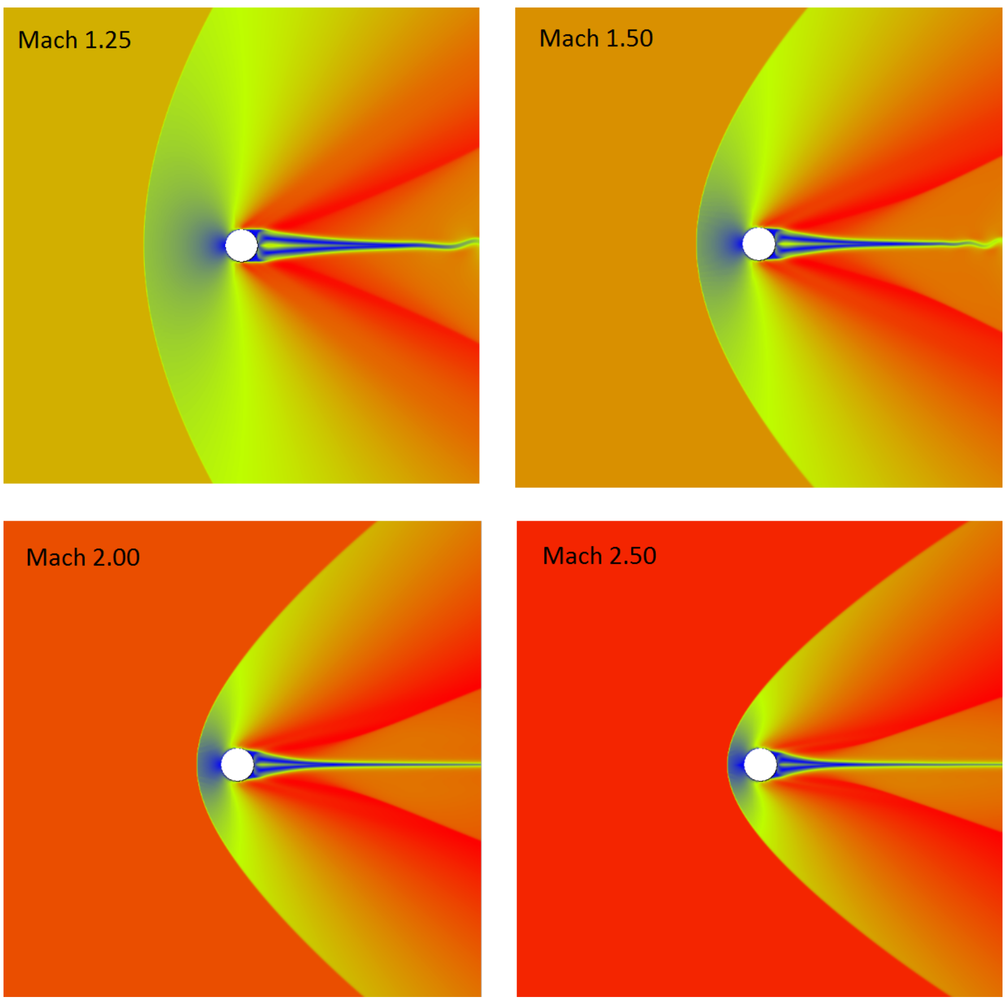

Figure 1: Verification study of front tracking code on supersonic flow around a cylindrical obstacle. The plots show the air pressure in simulations of four different Mach numbers.

Mach Number	Theoretical Distance	Simulated Distance
1.25	7.6667	7.667
1.50	3.0760	2.985
2.00	1.2406	1.370
2.50	1.0109	0.996

Figure 2: Comparison of the shortest distance from the shock front to the surface of the cylinder with theoretical values.

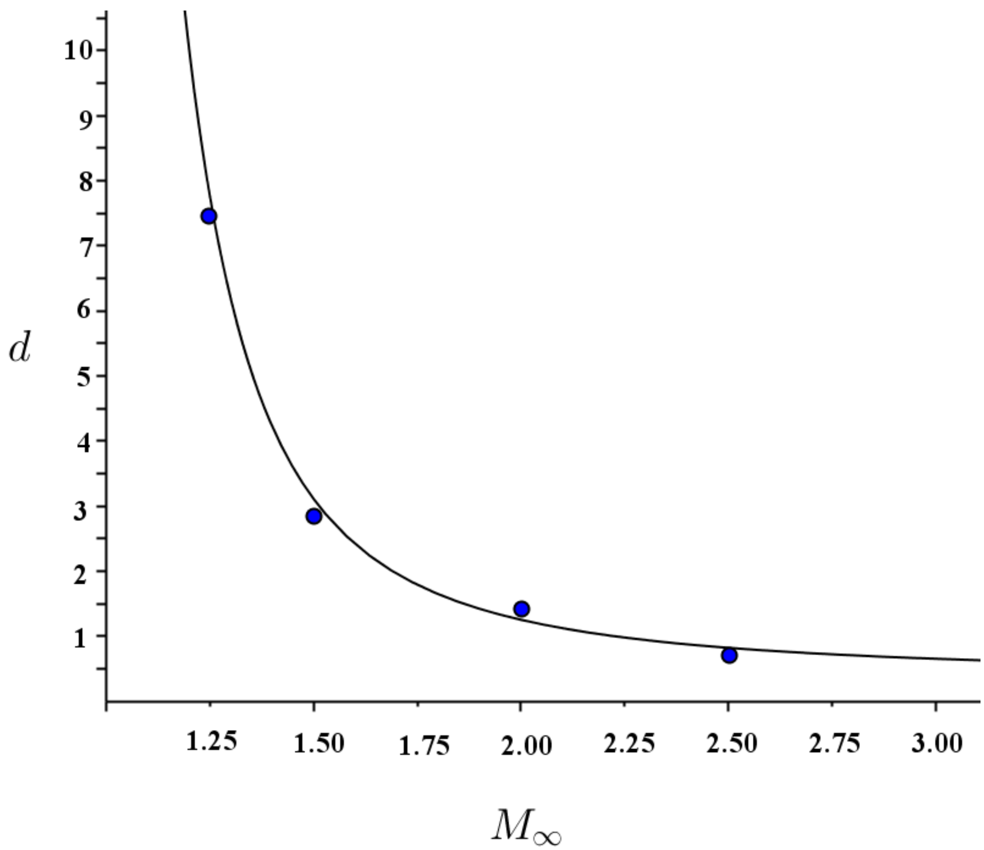

Figure 3: Comparison of the shortest distance from the shock front to the surface of the cylinder with theoretical curve.

On verification, Moore performed simulations on axially symmetric cylinder. He continued simulations for the NACA-0012, NACA-0015, WORTMANN-FX-76MP-120, and NACA-64A204 airfoils. By running various simulations for cylinders, we found an optimal grid size which gave us results that closely resemble those previously presented in [9, 8, 1] on the shape, curvature, and standoff distance of the bow shock. The comparison of supersonic flow around cylinder gave excellent agreement between theory and the numerical solution from the front tracking code. However, on simulations at transonic speeds, a converging solution requires computational mesh 20 times of refined mesh as in the supersonic cases. We attribute this shortcoming of the front tracking code due to the lack of enforcement of

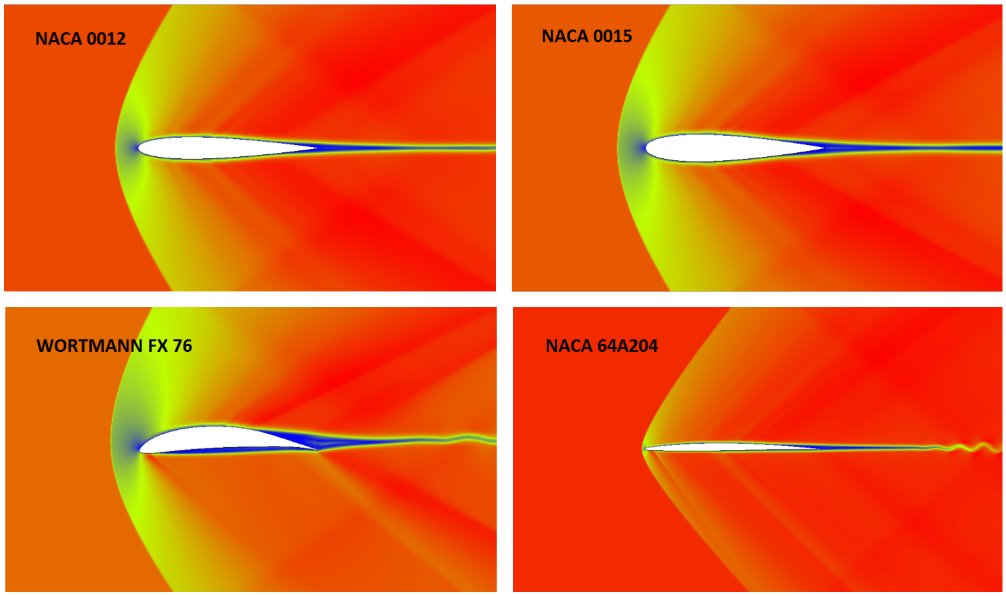

Figure 4: Pressure plot in simulations of bow shock formation for supersonic flow around different aircraft wings.

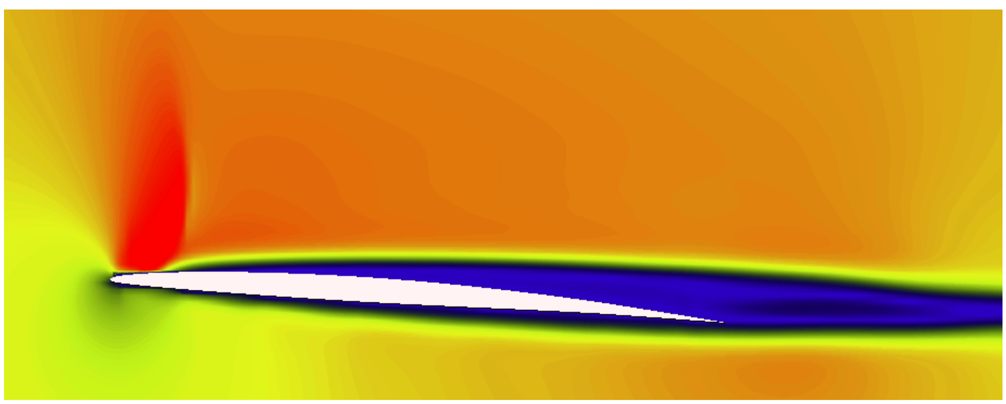

Figure 5: Pressure plot in the simulation of transonic shock on top of F-16 wing using the front tracking method.

mass conservation at both the external boundary and the aircraft wings. Although the study did not produce the desired result, it points to the direction for improvement of the front tracking code for the simulation of thin aircraft wings.

Figure 1, Figure 2, and Figure 3 show the result of the verification study on the shock formation in simulations of supersonic flow around a cylinder. Figure 4 shows the formation of bow shock in simulations of supersonic flow around different aircraft wings. Figure 5 is the pressure profile in the simulation of transonic flow around the wing of F-16 jet fighter.

3. Parachute Modeling

Previous studies on parachute mostly focus on the steady drag and velocity in the terminal descent regime and their dependence on parachute geometry, dimension and payload. In contrast to terminal descent, parachute inflation has a very short time duration, typically in a few seconds. However, this short period regime of parachute dynamics is a very important phase of the deceleration system. Any malfunction such as inversion, barber's pole, or jumper-in-tow could have serious effect on the fate of the personnel and cargo delivery. Parachute inflation is a complex problem involving aerodynamics, structure dynamics and elasticity. Researchers have studied parachute inflation with different methods including empirical analysis, semi-numerical simulation and experiment [10, 11].

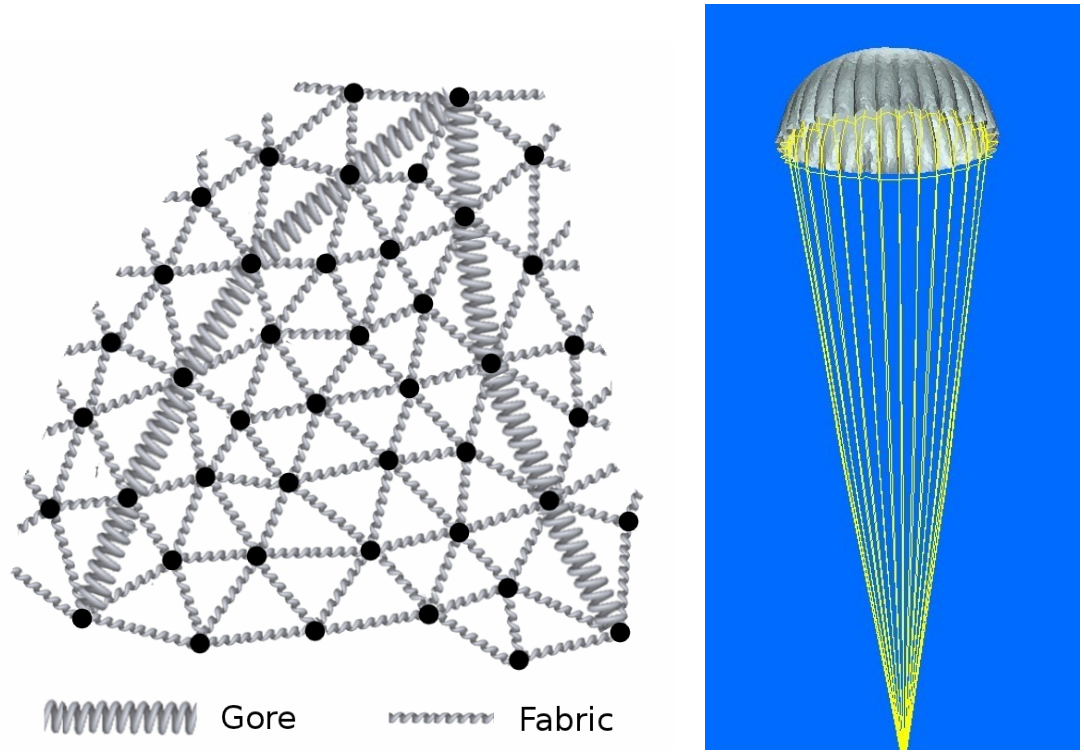

Figure 6: The left plot shows spring model on a triangulated mesh. Each vertex point in the mesh represents a mass point with point mass m. Each edge of the triangles has an equilibrium length set during initialization and the changing length exerts a spring force on the two neighboring vertices in opposite directions. Gores are added as curves with larger spring constant. The right shows the opened parachute through the spring model.

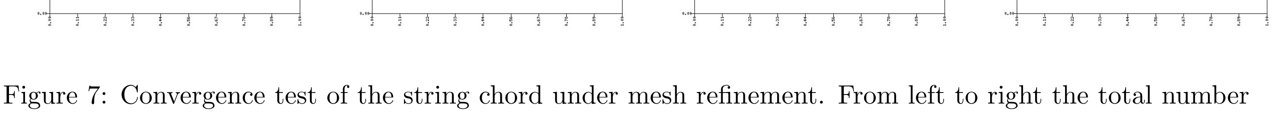

Figure 7: Convergence test of the string chord under mesh refinement. From left to right the total number of points in the string are 50, 100, 200, 400 respectively. The total mass of the string chord as well as the payload at the lower end are kept constant in the simulations.

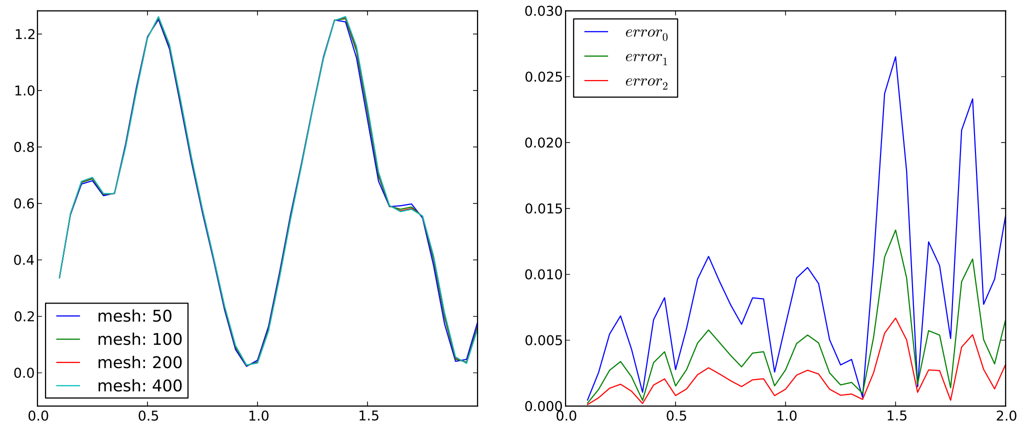

Figure 8: Convergence test results of spring model on string chord. In this test the string chord is fixed at one end while the other end has a payload and is free to move. The simulations are on the sequences with 50, 100, 200, 400 points respectively. The total mass $M = Nm$ is a constant in the simulation. The plots show the convergence of total kinetic energy of the system.

mesh size	e_l	e_k	e_p
50 and 100	0.00374	0.01664	0.03464
100 and 200	0.00184	0.00821	0.01726
200 and 400	0.000918	0.00406	0.008614

Table 1: Convergence tests of spring model for a swing chord. In the computational sequences, the total mass of the swing chord is fixed. As the number of points increases, the point mass is reduced accordingly. Cauchy error is calculated on two consecutive mesh sequences. Column e_l, e_k, and e_p are errors of total length, total kinetic energy and total spring potential energy, respective. The numerical results show the first order convergence for each of them.

Quantitative analysis of fabric aerodynamic deceleration system (ADS) is a challenging problem due to its complexity. An accurate numerical and computational platform of such system requires sophisticated technology in computational fluid dynamics, computational structure dynamics and fluid-structure interaction. We have approached the problem through the spring-mass fabric model. Figure 6 is a schematic plot of the spring-mass fabric model. In our previous papers [7, 6], we introduced the use of spring-mass system as a meso-scale model to mimic the dynamic motion of fabric surface and incorporate this model into the numerical modeling and simulation of parachute system. We showed that the system is a conservative system (without external force and damping) and the motion is purely oscillatory in the direction tangential to the fabric surface. We also proved that there exists an upper bound for the eigen-frequency of such oscillatory motion

$$\omega \leq \sqrt{\frac{2Mk}{m}},$$

where k is the spring constant, m is the point mass, and M is the maximum number of the neighbors a spring vertex point can have. The spring model preserves the property of a fabric surface with stiff elasticity but no bending energy. It reacts to compression force in tangential

mesh size	e_A	e_k	e_p
15 and 30	0.02528	1.91810	1.97967
30 and 60	0.01507	1.21784	1.21772
60 and 120	0.00604	0.53550	0.52837

Table 2: Convergence tests of spring model for a fabric drum. In the computational sequences, the total mass of the membrane is fixed. As the number of points increases, the point mass is reduced accordingly. Cauchy error is calculated on two consecutive mesh sequences. Column e_A, e_k, and e_p are errors of total area, total kinetic energy and total spring potential energy, respective. The numerical results show the first order convergence for each of them.

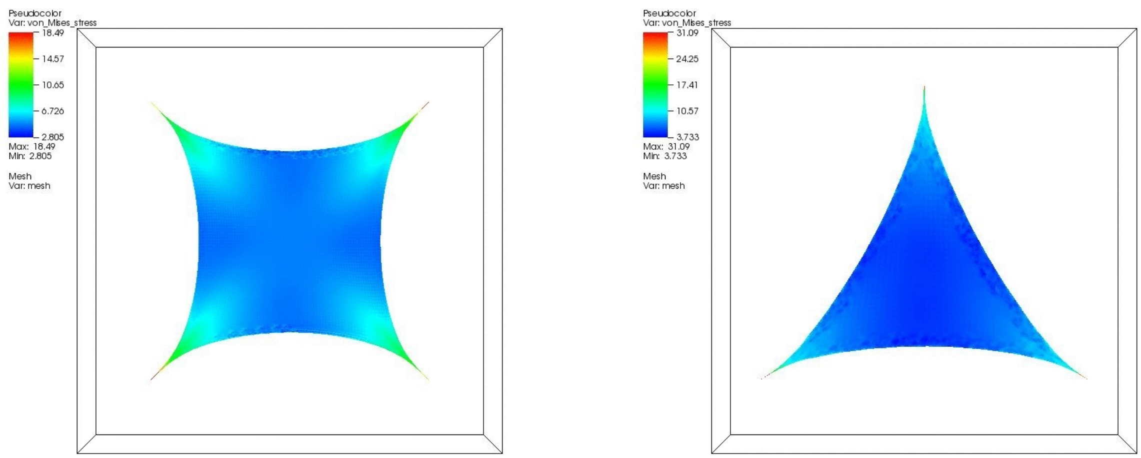

Figure 9: We use the von Mises formula Eq. (3) to calculate the fabric stress in the spring model. The plots show the von Mises stress of rectangular and triangular membranes when pulled from corners.

direction with realistic wrinkling. However, questions remain open as to whether such system is convergent when the computational mesh is refined, and if so, to what continuum model it converges. During this research visit, we carried out the convergence study and provided answer to the first part of the question, that is, the system is indeed convergent.

We have performed a series of numerical simulations for the fixed boundary string in two dimensions and membrane in three dimensions under computational mesh refinement. In both 2D and 3D simulations, we keep the spring constant of the string (2D) or membrane (3D) as a constant. We also keep the total mass, which is the summation of all point mass $M = Nm$, as a constant, here N is the total number of points and m is the mass of each mass point.

The Cauchy sequences are numerical solutions with increasing number of mass points (and segment). The 2D sequences are for total number of points $N = 50, 100, 200, 400$ respectively. We recorded characteristic variables of the simulation such as the total energy and length of each sequence. Figure 7 shows the string evolution under mesh refinements. The left plot of Figure 8 shows the change of total length and total kinetic energy of the string as functions of time. The right plot of the figure shows the error of each variable in the sequences. We also integrated the norm of error in both 2D and 3D over time and presented in Table (1) and Table (2). The numerical tests show that the sequences are indeed first order convergent.

Stress analysis on the parachute canopy and string chord during the inflation process is very important to the field test of the parachute. The natural stress on each side of the triangle in the spring model is the restoring force due to the stretching of each triangle side. Let τ_1, τ_2, τ_3 be the natural stress on side $1, 2, 3$ of a triangle, we have

$$\tau_i = k(L^i - L_0^i), \qquad i = 1, 2, 3, \tag{1}$$

where k is the spring constant, L_0^i is the equilibrium length of side i and L^i is the stretched length of the side i. This natural stress can be converted [] into the stress in Cartesian coordinates on the plane of the triangle. The Cartesian stress is a 2×2 tensor in the plane of the triangle

$$\sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{pmatrix}.$$

The conversion from natural stress to Cartesian stress is through a mapping matrix, that is

$$\begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{pmatrix} = \begin{pmatrix} c_1^2 & s_1^2 & s_1 c_1 \\ c_2^2 & s_2^2 & s_2 c_2 \\ c_3^2 & s_3^2 & s_3 c_3 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{pmatrix} \tag{2}$$

where $c_i = \cos\theta_i = dx_i/Li$ and $s_i = \sin\theta_i = dy_i/Li$ are the cosine and sine functions of the angle each side with the $x-$axis. The stresses in two principal directions are obtained via diagonalization of the stress tensor, that is

$$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{pmatrix} = T^{-1} \begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix} T,$$

where σ_1 and σ_2 are the solutions of the characteristic equation

$$\begin{vmatrix} \sigma_{xx} - \sigma_{1,2} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} - \sigma_{1,2} \end{vmatrix} = 0.$$

We use the von Mises stress

$$\Sigma_{vm} = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} \tag{3}$$

to measure the tension on the surface of the fabric. The safety factor of the material is defined as the ratio of the significant strength of the material to the von Mises stress. When this factor is decreased to a critical value (which corresponding to high stress of the fabric surface), it sends a warning signal for the design of the parachute canopy. Figure 9 shows the computed stress of rectangular and triangular membranes as we implemented during the summer visit.

We had two meetings with the parachute testing team led by Alec Dyatt. The parachute team made some vital comments on the direction of the parachute study. They suggested that our parachute validation should include shape comparison, attitude dependence, the varying angle of chute skirt with the airflow on the opening of the parachute, and the quantification of opening force on parachute payload. Under their suggestion we obtained the data of inflation drag on the C-9 parachute from Prof. Jean Potvin at St Louis University. Figure 10 shows the comparison of our front tracking simulation in comparison with Potvin's data on C-9 parachute.

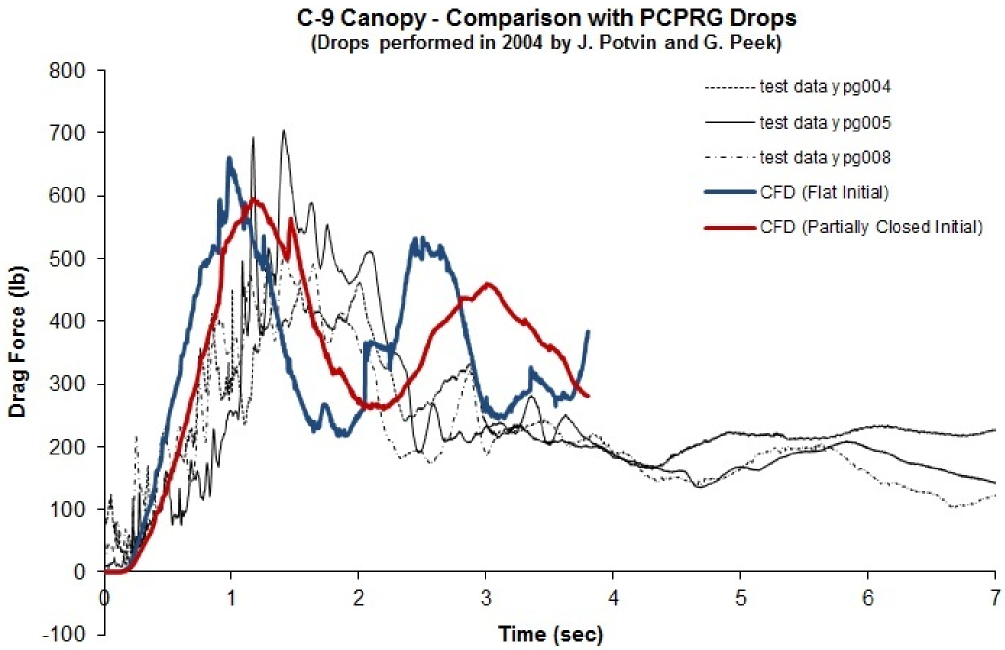

Figure 10: Evolution of drag during the inflation phase of C-9 personnel parachute. The experimental data is provided by Dr. Jean Potvin at St. Louis University.

4. Study of Airplane Icing

In-flight icing is the result of super-cooled water on the airframe. It can be in the form of cloud droplets or freezing rain/drizzle. Aircraft icing can adversely affect the flight characteristics such as increase drag, decrease lift, and can cause control problems. In worst case, it can cause the airplane to crash.

The Air Force testing center has the charter to test aircraft and weapons in all weather conditions including in icing conditions and in rain. They use the AIT (airborne icing tanker) to perform the artificial in-flight icing and rain testing. These tests are aimed to ensure that aircraft and weapons have capability to operate in the climatic extreme conditions.

The system consists nozzles for generating jets spray in the condition similar to icing and rain condition in flight. The testing is costly but necessary. Computer simulation, although cannot replace such tests, can provide useful information and carry out certain virtual testing at much lower cost.

At Edwards AFB, we communicated with the base scientists, Dr. Reasor and Mr. Bhamidipati about the capability of front tracking code in the study of phase transition problem such as deposition, dissolution, freezing and melting [4]. Figure 11 shows examples

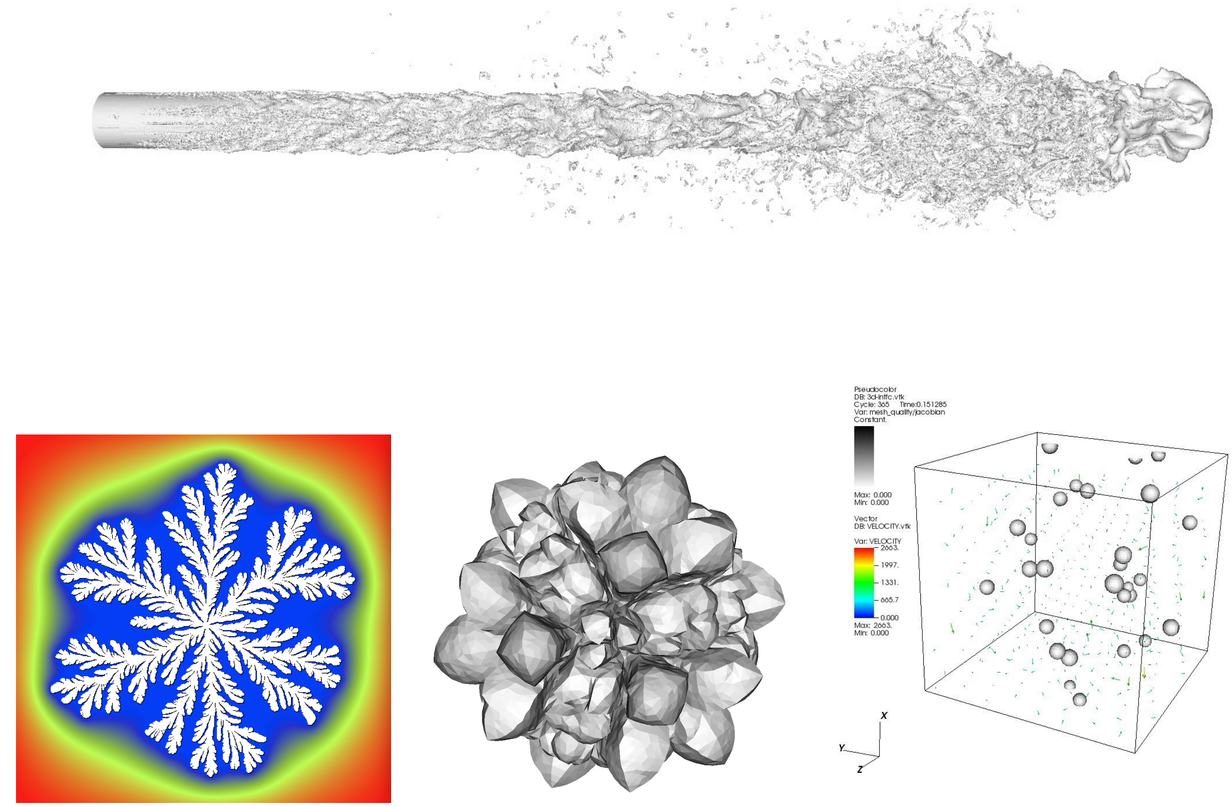

Figure 11: Front tracking simulation of jet spray, crystal formation, and collective motion of droplets. The inter-operable modules in the front tracking library is an ideal computational tool for airplane icing simulation.

of front tracking modules for simulations of jet spray and crystal formation. The interoperability of the front tracking modules makes it capable for the simulation of airplane icing test.

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